On the Direct Search for Spin-dependent WIMP Interactions

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We examine the current directions in the search for spin-dependent dark matter. We discover that, with few exceptions, the search activity is concentrated towards constraints on the WIMP-neutron spin coupling, with significantly less impact in the WIMP-proton sector. We review the situation of those experiments with WIMP-proton spin sensitivity, toward identifying those capable of reestablishing the balance.

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I. INTRODUCTION

The direct search for weakly interacting massive particle (WIMP) dark matter continues among the forefront efforts of experimental physics. The search is largely motivated by the continuing absence of a second positive signal with annual modulation confirming the result of the DAMA/NaI experiment despite significantly improved detectors, and especially following the several recent reports of possible indirect observation of dark matter annihilation [1, 2, 3].

Direct search efforts, based on the detection of nuclear recoils in WIMP-nucleon interactions, have been traditionally classified as to whether sensitive for the spin-independent or spin-dependent WIMP channel [4]. While the former are generally constructed simply on the basis of heavy target nuclei (since the interaction cross section varies as A^2), the latter require consideration of the spin structure of the detector nuclei and are customarily defined by whether the primary experiment sensitivity is to WIMP-proton or WIMP-neutron spin coupling. The main efforts to date have been in spin-independent searches, generally because the anticipated cross sections are larger owing to a coherent interaction across the nucleus. As recently noted by Bednyakov and Šimkovic [5], however, the importance of the spin-dependent sector cannot however be ignored: such searches provide twice stronger constraints on SUSY parameter space, permit the detection of large nuclei recoil energy due to nuclear structure effects in the case of heavy target nuclei, and prevent missing a dark matter signal which might be suppressed in the spin-independent sector. If the neutralino is predominantly gaugino or higgsino states, the coupling is only spin-dependent [6].

The above distinction in search efforts has become somewhat blurred, since many detector heavy isotopes also possess spin and even a small natural isotopic abundance can produce significant constraints. In fact, a single detector can simultaneously provide restrictions on both channels of the WIMP-nucleon interaction, but with sensitivity in each channel dependent on the nature of the detector material. The most stringent limits in the spin-dependent sector are currently provided by experiments traditionally considered spin-independent.

The future thrust of direct searches for WIMP dark matter is defined by a number of project upgrades and several new high profile activities. Basically designed for deeply probing the spin-independent phase space, these experiments project eventual sensitivities beginning well below the controversial DAMA/NaI result and extending to cross sections as small as 10^{-10} pb in the WIMP-nucleon interaction. We here consider the impact of this activity thrust on the spin-dependent sector, finding that of those experiments with spin-sensitivity, most all will provide increasingly improved restrictions predominantly on the possible WIMP-neutron spin coupling, with significantly less impact on the WIMP-proton coupling. This latter sector is in fact observed to have previously received comparatively little direct experiment attention, with the current restrictions derived from NaI experiments already surpassed by two orders of magnitude in sensitivity by the indirect searches [7, 8]. Given that there however remain important theoretical questions regarding the extraction of the indirect results, we examine the situation of direct experiments with predominantly WIMP-proton spin sensitivity, towards identifying those with capacity to provide similar restrictions.

Sec. II reviews the current experimental situation and thrust of new initiatives in the search effort. The impact of these is discussed in Sec. III, and summarized in Sec. IV.

II. EXPERIMENTAL SITUATION

The situation for spin-dependent (SD) activity is shown in Fig. 1 at 90% C.L. for a WIMP mass (M_W) = 50 GeV/c^2, obtained in a model-independent, zero momentum transfer approximation [9, 10]. The a_p, a_n are the WIMP-proton (neutron) coupling strengths in the spin-dependent WIMP-nucleus cross section

$$\sigma_A^{(SD)} = \frac{32}{\pi} G_F^2 \mu_A^2 (a_p\langle S_p\rangle + a_n\langle S_n\rangle)^2 \frac{J+1}{J}, \qquad (1)$$

where $\mu_{p,n,A} = \frac{M_W m_{p,n,A}}{M_W + m_{p,n,A}}$ is the WIMP-proton (-

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neutron,-nucleus) reduced mass, $\langle S_{p,n}\rangle$ is the expectation value of the proton (neutron) group spin, G_F is the Fermi coupling constant, and J is the total nuclear spin. The figure is constructed from the published results of the respective experiments, using

$$\sum_A \left(\frac{a_p}{\sqrt{\sigma_p^{lim(A)}}} \pm \frac{a_n}{\sqrt{\sigma_n^{lim(A)}}} \right)^2 \le \frac{\pi}{24 G_F^2 \mu_p^2}, \quad (2)$$

with $\sigma_{p,n}^{lim(A)}$ the proton and neutron cross section limits defined by

$$\sigma_{p,n}^{lim(A)} = \frac{3}{4} \frac{J}{J+1} \frac{\mu_{p,n}^2}{\mu_A^2} \frac{\sigma_A^{lim}}{\langle S_{p,n}\rangle^2}, \quad (3)$$

where σ_A^{lim} is the upper limit on $\sigma_A^{(SD)}$ obtained from experimental data, and the small difference between m_p and m_n is neglected. The sum in Eq. (2) is over each of the detector nuclear species, with the sign of the addition in parenthesis being that of $\langle S_p\rangle/\langle S_n\rangle$, and is an ellipse except in the case of single-nuclei experiments for which the ellipse degenerates into a band. When $\sigma_{p,n}^{lim(A)}$ were not available, they have been obtained from published cross section limits as described in Ref. [9, 11].

At this magnification, with the exception of CDMS/Ge, the exclusion plot is seen to consist of essentially horizontal (a_p-sensitive), vertical (a_n-sensitive) and diagonal bands, within which lies the allowed area, the exterior being excluded.

The CDMS results derive from the use of the nonzero momentum transfer analysis of Ref. [36] (the CDMS/Si result, not shown, constitutes a near-vertical band at $|a_n| \sim 1.5$, overlapping to some extent the results of EDELWEISS and DAMA/Xe-2). Note that the zero momentum transfer approximation does not simply set the nuclear structure form factor appearing in the differential WIMP-nucleus scattering rate to 1: the calculation of σ_A^{lim} involves dividing the experimental upper limit on the WIMP rate by the convolution over the detector recoil energy range of the form factor with the average inverse WIMP velocity. Some experiments use a form factor independent of $a_{p,n}$ as suggested in Ref. [4], such that σ_A^{lim} is also independent of $a_{p,n}$. Other experiments (such as [22, 37]) employ form factors dependent on $a_{p,n}$ (*e.g.*, those of Ref. [38]) and the σ_A^{lim} in Eq. (3) is not the same for $\sigma_p^{lim(A)}$ as for $\sigma_n^{lim(A)}$. When $\sigma_{p,n}^{lim(A)}$ have been published [22, 39, 40], it is straightforward to use them in Eq. (2) to obtain zero momentum transfer exclusions. Provided that the form factor is not changed, changing to a nonzero momentum transfer analysis of the same data leaves the (a_p,0) and (0, a_n) points fixed, while rotating the major axis of the ellipse, generally towards the nearest coordinate axis because the absolute value of the coefficient of $a_p a_n$ is lowered. In particular, for a single sensitive nucleus the coefficient of $a_p a_n$ is generally less than twice the geometric average of the coefficients of $a_{p,n}^2$. This removes the degeneration of the ellipses to infinite bands predicted by the zero momentum transfer framework for single nuclei experiments.

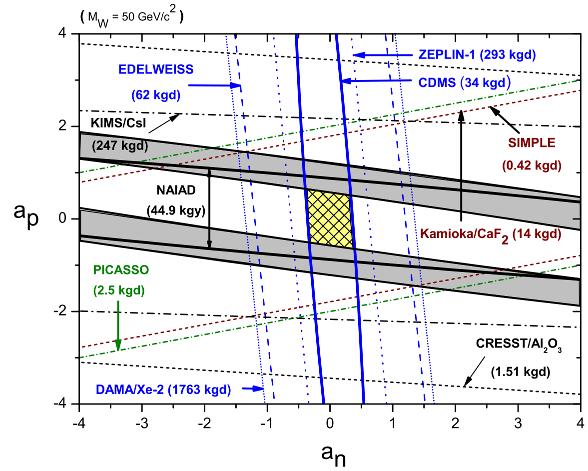

FIG. 1: spin-dependent exclusions for various direct search activities, the region permitted by each experiment lying inside the respective band: DAMA/Xe-2 (small dot), EDELWEISS/Ge (long dash), ZEPLIN-1/Xe (big dot), CDMS/Ge (solid), NAIAD/NaI (solid), PICASSO/C_4F_{10} (dash-dot), SIMPLE/C_2ClF_5 (short dash), Kamiokana/CaF_2 (short dash), CRESST-1/Al_2O_3 (short dash), KIMS/CsI (dash-dot); the controversial positive result of DAMA/NaI is shown as shaded. The unexcluded region, defined by the intersection of CDMS [25] and NAIAD [22], is shown as crosshatched.

Fig. 1 includes the results from CRESST-I/Al_2O_3 [18], several recently-reported fluorine-based experiments, and heavy nuclei searches normally considered spin-INdependent, such as EDELWEISS [41], ZEPLIN-I [39] and CDMS [25]; 50 GeV/c^2 is chosen since it lies near the maximum sensitivities of the various experiments: for larger or smaller M_W, all results are generally less restrictive, and vary differentially. Each experiment is identified with the full detector exposure in achieving the limit, rather than the normally-quoted effective exposure (spin-sensitive detector mass × measurement time), in order to make clear the difference between detectors with 100% spin sensitivity material and those with less. Also note that the results of the indirect searches [7, 8], which have been recently used to set very restrictive limits on the WIMP-proton coupling [36, 42], are not included. The 3σ C.L. observation of the DAMA/NaI annulus, appearing as two shaded bands, is taken from Ref. [21], which uses the standard halo model and Nijmegen form factor, spin matrix elements [38]. Although this report is from only a 159 kgy exposure, the most recent DAMA/NaI [37] result confirms the same amplitude and phase of the annual modulation, simply refining the error bars; as a consequence, the shell decreases in thickness without shrinking.

As evident from Fig. 1, the intersection of any two

TABLE I: spin-sensitive detector isotopes and their experiments.

isotope	Z	J^{π}	abundance (%)	experiment
^{3}He	2	$1/2^{+}$	<<1	MIMAC [12]
^{7}Li	3	$3/2^{-}$	93	Kamioka/LiF [13]
^{13}C	6	$1/2^{-}$	1.1	PICASSO [14], SIMPLE [15], COUPP [16]
^{17}O	8	$5/2^{+}$	<<1	ROSEBUD [17], CRESST [18]
^{19}F	9	$1/2^{+}$	100	SIMPLE [15], PICASSO [14], Kamioka [13, 19], COUPP [16]
^{21}Ne	10	$3/2^{+}$	<<1	CLEAN [20]
^{23}Na	11	$3/2^{+}$	100	DAMA [21], NAIAD [22], ANAIS [23], LIBRA [24]
				Kamioka/NaF [19]
^{27}Al	13	$5/2^{+}$	100	ROSEBUD [17]
^{29}Si	14	$7/2^{+}$	4.7	CDMS [25]
^{35}Cl	17	$3/2^{+}$	76	SIMPLE [15]
^{37}Cl	17	$3/2^{+}$	24	SIMPLE [15]
^{43}Ca	20	$7/2^{-}$	<<1	CRESST-II [26], Kamioka/CaF_2 [27]
^{67}Zn	30	$5/2^{-}$	4.1	CRESST-II [26]
^{73}Ge	32	$9/2^{+}$	7.8	HDMS [28], CDMS [25], GENIUS [29], EDELWEISS [30]
^{127}I	53	$5/2^{+}$	100	DAMA [21], NAIAD [22], KIMS [31], ANAIS [23]
				LIBRA [24], COUPP [16]
^{129}Xe	54	$1/2^{+}$	26	ZEPLIN [32], XENON [33], XMASS [34], DRIFT [35]
^{131}Xe	54	$3/2^{+}$	21	ZEPLIN [32], XENON [33], XMASS [34], DRIFT [35]
^{133}Cs	55	$7/2^{+}$	100	KIMS [31]
^{183}W	74	$1/2^{-}$	14	CRESST-II [26]
^{209}Bi	83	$9/2^{-}$	100	ROSEBUD [17]

search results, one of which is predominantly a_p-sensitive and the other a_n, yields more restrictive limits than either of the two alone. Clearly, the spin-independent group of experiments is efficient in reducing the allowed spin-dependent parameter space, despite the small (7.8%) component of spin-sensitive ^{73}Ge isotope in the case of CDMS and EDELWEISS (see Table I). In Fig. 1, the predominantly WIMP-neutron sensitivity of CDMS/Ge is seen to reduce the range of $|a_n|$ allowed by NAIAD by more than a factor 30 (with a small reduction in $|a_p|$), corresponding to the cross section limits of $\sigma_p \leq 0.320$ pb; $\sigma_n \leq 0.166$ pb obtained via Eq. (1) rewritten for a single nucleon.

The future thrust of direct search activity is defined by a number of traditionally-classified spin-independent project upgrades, including ZEPLIN-MAX/Xe [32], CRESST-II/$CaWO_4$ [26], LIBRA/NaI [24], EDELWEISS-II/Ge [43], GENIUS/Ge [29], superCDMS/Ge [44], HDMS/^{73}Ge [28], KIMS/CsI [31], WARP/Ar [45] and ELEGANT VI/CaF_2 [24]. New high profile projected activity includes XENON/Xe [33], XMASS/Xe [34], EUREKA (CRESST-II+EDELWEISS-II) [30], COUPP/CF_3I [16], CLEAN/Ne [20], DRIFT/CS_2 [35], ArDM/Ar [46], DEAP/Ar [47] and MIMAC/He [12]. It is not our point to review in detail these efforts: descriptions exist as indicated and elsewhere [6, 24]. Suffice it to mention, with the exception of the light noble liquid projects, all are "heavy" in the sense of A. Most all of the cryogenic activities envision eventual detector masses of up to 500 kg; the noble liquid activities, 1-10 ton. As evident, the new activity emphasis appears to have shifted from cryogenic searches to scintillators employing noble liquids, reflecting a shift from phonon+ionization to ionization+scintillation discrimination techniques in identifying and rejecting backgrounds, as well as providing directional sensitivity. The current background levels are $\sim 10^{-1}$ evt/kgd; projections for the new devices range to $\sim 10^{-2}$ evt/kgy. Generally, the bolometers have a few-keV recoil threshold capacity, in contrast to the $>$ 10 keV thresholds of the noble liquid experiments; since the Na presence permits DAMA/NaI to observe a signal below the Ge recoil thresholds of CDMS and EDELWEISS, the strong reduction of the spin-independent parameter space still compatible with the DAMA/NaI signal disappears at masses below ~ 20 GeV/c^2. The recent CDMS Si-based measurement [48] further reduces this region by more than a factor two, but does not yet eliminate it.

III. DISCUSSION

The spin-dependent nuclei of the above experiments are shown in Table I. As evident, not all of the above experiments will contribute to further constraining this

sector, in particular those based on argon which lacks spin-sensitive isotopes.

The problem with the above activity thrust for spin-dependent investigations is shown in Fig. 2, with the projected experimental limits of the $|a_n|$ sensitive experiments (ZEPLIN, CRESST-II, EDELWEISS-II, superCDMS, HDMS, XENON, XMASS) subsumed under the label "future" suggested by a superCDMS projection [44], and intended only to serve as an indication of the general impact to be anticipated from the above activity (note the change in the a_n scale). The currently allowed area in the parameter space of Fig. 1 is indicated by the shaded area, and suggests the reduction in the allowed a_p - a_n space to be achieved with the "future" thrust: generally, the limiting ellipses of all will shrink in both parameters, but with the bounds on $|a_p|$ still an order of magnitude larger than $|a_n|$.

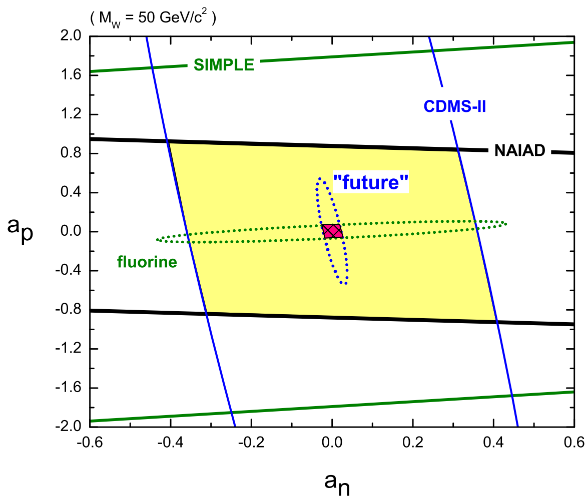

FIG. 2: general projections (at $M_W = 50$ GeV/c^2) of results to be expected from the current experimental direct search activity, in comparison with the current a_p-sensitive experimental results. The near-vertical ellipse denoted by "future" and suggested by phase A of superCDMS [44] indicates the general improvement to be achieved by the a_n-sensitive experiments discussed in the text. The near-horizontal ellipse indicates a similar projection for the fluorine-based experiments (obtained from a 200 kgd projection of the current SIMPLE result), with the croshatched area indicating the intersection of the two; the crosshatched region of Fig. 1 is now shown as shaded.

The point of any search experiment is however discovery, which will be exacerbated should one or more of the spin-independent "future" experiments obtain a positive signal. This is illustrated schematically in Fig. 3 for the case of two "discoveries", NaI and "future". The four allowed a_p−a_n regions (shaded), defined by the intersection of the hypothetical new positive result from the "future" experiments with that of NaI (corresponding to two regions of $\sigma_p - \sigma_n$), will require at least one additional and different detector experiment of sufficient sensitivity to further reduce the parameter space to two allowed areas corresponding to a single pair of cross sections.

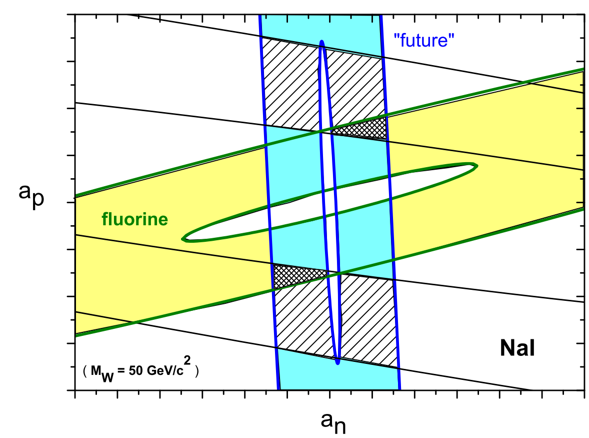

FIG. 3: schematic of a positive result in one of the "future" experiments (shaded), intersecting (hatched) that of a positive NaI result. The parameter space shown as crosshatched represents the area allowed by the intersection of NaI, "future" and a similar positive result from one of the fluorine-based experiments.

Both NAIAD [22] and DAMA/NaI are ended. As evident, without some additional effort, the direct search restrictions on a_p would remain essentially unchanged from those provided by these measurements. The DAMA/NaI experiment has been replaced by DAMA/LIBRA [24], an upgrade of the NaI experiment to 250 kg with improved radiopurity, running since 2003. The mass increase however provides only a factor 2.5 decrease in the exposure necessary to confirm the original DAMA/NaI signal, with further improvement in Fig. 2 scaling as $\sqrt[4]{\text{exposure}}$; R&D is in progress for a mass upgrade to 1 ton. A second NaI experiment, ANAIS, reports an exposure of 5.7 kgy with a 10.7 kg prototype [23], and will be eventually upgraded to 100 kg. It is however only projected to repeat the DAMA/NaI measurements for confirmation of the annual modulation.

All of these experiments rely on pulse-shape analyses for discrimination of backgrounds. All appear to require, relative to the leading a_n-sensitive experiments, exceedingly large exposures, despite active masses significantly larger than the bolometer experiments of the a_n sector. To further limit a_p via direct observation, one or more experiments with improved WIMP-proton sensitivity is required.

A. Other a_p-sensitive measurements

The KIMS experiment, based on CsI, has recently reported competitive spin-independent limits with a 247 kgd exposure. Since its sensitivity is similar to NaI, we show in Fig. 1 the corresponding spin-dependent constraints as recalculated from the raw data in Ref. [31],

after first reproducing the reported spin-independent exclusion. Lacking any calculated $< S_{p,n} >$, the result is obtained using an odd group approximation (OGA), and the spin-dependent form factor of Ref. [4]. The small gyromagnetic ratio of ^{133}Cs yields $< S_p > \sim$ -0.2, near that of ^{23}Na (recall that the spins enter quadratically), although the higher J of Cs implies a factor 77% reduction in Eq. (1). To achieve the level of NAIAD, an exposure of 25.1 kgy would be required with the current background level and discrimination; the experiment is to be upgraded to 80 kg.

As seen in Fig. 1, CRESST-I achieved [18] a competitive result with only a 1.51 kgd exposure of a 262 g Al_2O_3 bolometer, and could achieve the level of NAIAD with a factor 50 less exposure ($\sim$ 300 kgd). It has however been abandoned in favor of $CaWO_4$ (CRESST-II), which is primarily a_n sensitive through its naturally abundant 14.3 % ^{183}W, 0.14% ^{43}Ca and 0.038% ^{17}O isotopes [49]. The main spin-dependent sensitivity derives from the almost negligible $^{43}Ca+^{17}O$, the small gyromagnetic ratio of ^{183}W pointing to a negligible spin-dependent OGA sensitivity ($\langle S_n \rangle \sim 0.031$); the current CRESST-II result lies near $|a_n| \leq 20$, well outside Fig. 1.

Several activities based on new prototype devices have been recently reported. ROSEBUD includes an Al_2O_3 bolometer, but the device is only 50 g [17] and assuming the same sensitivity as CRESST-I would require almost 16 years exposure to achieve the current NAIAD limits. A mass increase to 1 kg would enable limits on a_p similar to, and more restrictive than, the current NAIAD result with a relatively short time exposure of $\sim$ 0.8 y. Like CRESST-II [49], ROSEBUD however pursues scintillating bolometers to further reject backgrounds, which if successful could yield restrictions on a_p equivalent to those of NAIAD with as little as a 2 kgd exposure.

ROSEBUD also pursues measurements in BGO (= $Bi_4Ge_3O_{12}$). As seen in Table 1, although Ge and O are both neutron-sensitive, Bi is proton-sensitive. As with ^{183}W however, a small ^{209}Bi gyromagnetic ratio yields an OGA estimate of $< S_p > \sim$ -0.085. Successful scintillation discrimination in this case could also yield results equivalent to those of NAIAD (although a 200 kgd exposure would be required).

The Kamioka/CaF_2 scintillator experiment of Fig. 1 reports a new, very competitive limit with a total 14 kgd exposure of a 310 g device [27], realized via careful attention to component intrinsic radioactive backgrounds. It surpasses both bolometer-based Kamioka/NaF [19] and Kamioka/LiF [13]. The background rate is however still roughly a factor 10 higher than those of the NaI experiments, and may limit the future performance of the detector. The recently ended ELEGANT VI is being replaced by CANDLES III, but both are primarily focused on $\beta\beta$ decay and have yet to provide a WIMP exclusion.

The Kamioka/CaF_2 result is essentially equivalent to recent results reported by the two superheated droplet detector (SDD) experiments (SIMPLE/C_2ClF_5 [15], PICASSO/C_4F_{10} [14]), with significantly less active mass and exposure owing to inherent SDD background insensitivity. These have so far received little attention, most likely because of only prototype results having so far been reported, with an unfamiliar technique. Nevertheless, given their current results, they offer significant room for rapid improvement in parameter space restrictions. This is shown in Fig. 2 by "fluorine" for a 10 kgd exposure with background level of 1 evt/kgd (the Kamioka/CaF_2 experiment would require 34.5 kgy exposure with current sensitivity to achieve the same limit, requiring either significant detector mass increase and/or improved background discrimination to remain competitive). Being also comparatively inexpensive and simple in construct, large volume SDD efforts may easily be envisioned (a 2.6 kg, 336 kgd exposure PICASSO effort is in progress, which if successful will further reduce the crosshatched area of Fig. 2).

The simplicity argument is similarly true for COUPP [16], which is based on a 2 kg CF_3I bubble chamber with the background insensitivity of the SDDs. In this case, the 10 kgd exposure could be achieved more quickly since the CF_3I-loading of a SDD is only 1% in volume [50]. The COUPP technique however requires a significant extension of the metastability lifetime of the refrigerant beyond previous bubble chamber technology. This has apparently been addressed with some success [16], but a first result is still lacking.

In either case, given sufficient exposure, the fluorine experiments combined with current CDMS results have the ability to severely constrain the currently allowed parameter space of Fig. 1.

B. Spin Sensitivities

The above complementarity of various experiments of differing orientation in the parameter space is strongly governed by the spin matrix elements of the involved nuclei. Unfortunately, many of the new projected experiments lack specific spin matrix element calculations; in their absence, several of the results are obtained from an odd group approximation (OGA). This approximation strictly allows only a WIMP-proton or WIMP-neutron sensitivity, by assuming the even group to be an inert spectator so that the WIMP interacts with only the odd group of detector nucleons. This is reflected in the traditional spin-dependent exclusion plots, in which for $< S_p >= 0$, only a_n is constrained.

In the OGA, an experiment using only odd Z isotopes cannot constrain the WIMP-neutron coupling. Nuclear structure calculations however show that the even group of nucleons has a non-negligible (though subdominant) spin. An example is ^{39}K, which surprisingly possesses $< S_n > = 0.05$ [51] in spite of having a magic number of neutrons (closed neutron shell). This can be understood because the gyromagnetic ratio of the nucleus is low compared to that of the nucleon, indicating a dominant contribution from the orbital angular momentum

of the proton structure; when Z $\approx$ N and large, if the protons have a high angular momentum, so also will the neutrons in general.

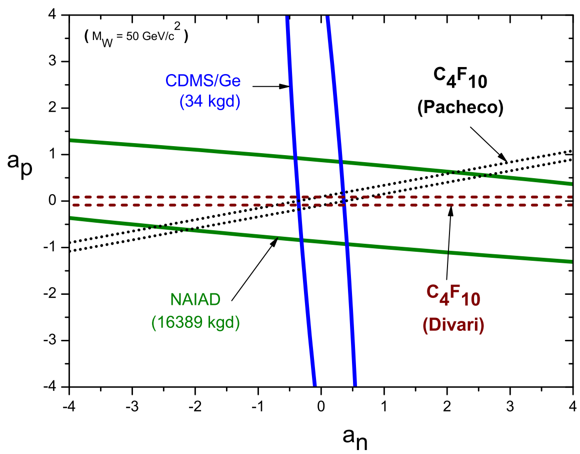

FIG. 4: exclusion comparison for C_4F_{10} for each of two sets of fluorine (^{19}F) spin matrix elements [52, 53], for a zero event 30 kgd exposure.

For A $<$ 50, the OGA has been extended by including additional information regarding the β decay ft values and measured magnetic moments of mirror pairs for nuclear systems [54], which provides nonzero estimates of the spin matrix element for the odd group, with seemingly small variations in the odd group spin matrix element.

Generally, the OGA yields $< S_{p,n} >$ significantly different from the model calculations. The refined $< S_{p,n} >$ of nuclear structure calculations are however not measured, but obtained from various nuclear models which reproduce known nuclear data, so that different sets of results may exist for the same nuclide. In some cases (^{23}Na, ^{35}Cl), there is even a sign reversal. Some indication of the impact of the model difference on the contour orientation is seen in Fig. 4, for an otherwise identical 30 kgd projection with C_4F_{10} assuming full discrimination.

For heavy nuclei, and/or heavy WIMPs, the zero momentum transfer approximation breaks down and the finite momentum transfer must be taken into account, as discussed extensively in Ref. [55]. In general this involves consideration of the nuclear form factor (F) in the interaction scattering rate

$$\frac{dN}{dE_r} \sim \mu^{-2} M_W^{-1} \sigma_A^{(SD)} F^2(q) \int_{v_{min}}^{v_{max}} \frac{f(v)}{v} dv, \qquad (4)$$

where $f(v)$ is related to the velocity distribution of halo WIMPS, v_{min} is the minimum incident WIMP speed required to cause a recoil of energy E_r, v_{max} is the maximum incident WIMP speed, and $F^2(q) = \frac{S^A(q)}{S^A(0)}$ with the S^A related to the a_p, a_n by $S^A(q) = (a_p + a_n)^2 S_{00}(q) + (a_p - a_n)^2 S_{11}(q) + (a_p + a_n)(a_p - a_n) S_{01}(q)$. Calculations of the structure functions S_{jk} so far have included only ^{19}F, ^{23}Na, ^{27}Al, ^{29}Si, ^{73}Ge, ^{127}I, and $^{129,131}Xe$, and the results for the same isotope differ significantly among calculations, depending on the nuclear potential employed [55].

IV. CONCLUSIONS

The future search for "spin-independent" WIMP dark matter is particularly well-motivated and directed towards improvements of several orders of magnitude in probing the phase space; due to the spin sensitivity of several of the new detector isotopes, it will also provide significant impact in the a_n sector of the "spin-dependent" phase space.

In contrast, the direct search in the a_p sector is somewhat neglected. This seems particularly strange given that the spin-sensitivity of fluorine is well-known and that several fluorine-based prototype experiments (LiF, NaF, CaF_2) have been reported over the years. At present, new experiments based on Al_2O_3 and fluorine are seen as possibly capable of providing restrictions on a_p surpassing those from NaI and complementary to those to be obtained on a_n. Of these, the SDD and bubble chamber experiments appear to offer the greatest possibility of achieving significantly improved restrictions with least exposure, given their intrinsic insensitivity to most common backgrounds; being also relatively simple in construct and less expensive by at least an order of magnitude, large volume efforts are readily possible. None of these experiments however seem receiving of attention comparable to those of the a_n activity, which will prove problematic should any of the latter in fact observe a positive signal in the near future.

The projected impact of several of the new, possibly interesting spin-dependent projects, such as $CaWO_4$, BGO and CsI, suffer from the availability of only OGA estimates of their spin values, which constrains *a priori* their orientation in the parameter space, and could profit from more detailed nuclear structure calculations.

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